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Developing a conceptual framework to evaluate effectiveness of emergency response system for oil spill

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Abstract: The increase of oil spill accidents has made significant impacts on life, property and the environment. Facing ever-increasing risk of disaster losses, how to cope with and response to large scale oil spill disaster effectively is becoming more and more important. And it is extremely onerous and arduous to develop a highly capable assessment technique to evaluate the effectiveness of emergency response system (ERS) for oil spill. An ERS for oil spill is a complex and dynamic system comprising a number of elements, one of which fails to accomplish its function would result in potential adverse impacts on the whole system. Evaluating the effectiveness of the system requires the consideration of all failures identified in the system simultaneously. Aims to propose a decision-making framework, this paper uses failure mode effect and criticality analysis (FMECA) to evaluate the effectiveness of ERS to make improvements in oil spill emergency management. It is achieved by analysing the components and bounds of the system, identification of generic failure modes which are considered as key factors of ERS for oil spill. And lastly a case study is demonstrated to validate the methodology framework.

Key words: emergency response system (ERS); oil spill; effectiveness; FMECA

1 Introduction

According to the statistics of Clarkson Research Services Limited, the total oil tanker fleet is up to 493 million tons by the end of 2012. The development of vessel traffic increases the occurrence probability of oil spill, and the significant impacts on local economies and environment. In April 2010, the British Petroleam licensed transocean drilling rig deepwater horizon sank in the Gulf of Mexico took away eleven lives and sent over 200 million gallons of oil into the water (Alijani et al. 2012). An oil spill disaster of a pipeline explosion at port of Dalian, north-east of China, happened in 2010. 1500 tons of oil spilled from the pipes created 180 km^2 slick in the Yellow Sea, which grew to 430 km^2 later (The Huffington Post 2010). The container ship "Cosco Busan" slammed into a bridge tower in 2007, which was not

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handled effectively because the officials misjudged the severity of the oil spill, and more than 50000 gallons of oil spilled in the bay (Fimrite 2007).

Facing ever-increasing risk of disaster losses, how to cope and deal with large scale oil spill disaster effectively is becoming more and more important. It is a system engineering involved in many subsystems which act as prevention, mitigation, preparation, response and recovery. An emergency response system (ERS) for oil spill is designed to assess, react, and recover an emergency as quickly and effectively as possible. It comprises a series of interrelated and interdependent subsystems and activities to complete the tasks in the ERS for oil spill.

The effectiveness evaluation of ERS for oil spill can measure the expected objectives achievement, and detect the failures in response. A recent reviews demonstrate that there are many literatures and research highlights of the importance of ERS. However, relative scarcity of the literature on the effectiveness evaluation of ERS is emphasized, and the area of ERS for oil spill is particularly underdeveloped.

Some literatures only focus on the part of the ERS, which includes coordination between the military and civilian organizations during emergency (Salmon et al. 2011), the importance of updating information during the emergence response (Vivacqua and Borges 2012), the improvement of the response time to increase the effectiveness of ERS (Mustaffa and Kazunori 2012), effectiveness of response team features (Leach and Mayo 2013), the effectiveness of training in organizations(Winfred et al. 2003), the stakeholders' perspective of prioritizing oil spill objectives (Tuler and Webler 2009), and post-incident assessment of environmental contamination and damage (Kirby and Law 2010). However, the emergency response comprises a series of interrelated and interdependent components and activities. The increased performance of single component can't represent for the increase of the whole system. It is necessary to break the system into "pieces" to find its failure and potential causes, but most important is from the system perspective to analyze how these "pieces" fit together to reach the goal of the system.

Other literatures highlight the effectiveness of ERS from the view of system engineering. Abrahamsson et al. (2010) built a framework to evaluate the effectiveness of ERS and exemplified by a power supply system; Smith and Clark (2006) used the combination of Value Focused Thinking (VFT) and BN influence diagram to model the effectiveness between the system components, which needed large amount of precise information to define the prior probability. Jackson et al. (2010) used FMECA to evaluate the reliability of ERS and took chlorine release as an example based on historic data. It is relative easy to evaluate the effectiveness of ERS based on the historic data. However, the data are usually insufficient for oil spill, which usually appears randomness and vagueness with high uncertainty, and some data are confidential.

Oil spill disaster is considered to be unpredictable because of number of people involved, short decision in limited time, unavailability of resources, uncertainty about the situation, pressure and stress involved, and damage to the sea environment (Vivacqua and Borges 2012). Consequently, effectiveness evaluation of ERS detected from past accidents provides an insight of problems might happen in future (Jackson et al. 2011), no matter the corporation mechanism running smoothly or not, or how the performance of emergency manager is (Hockings et al. 2006). Uhr et al. (2005) develops a metric to evaluate the effectiveness of ERS, which includes saving of lives and property, the efforts of responders to aid casualties, the response time period, and the safety of the response with respect to responders. However, this metrics is too rough to reflect the ERS operation. The emergency response process is dynamic and full of uncertainties. It is, therefore, necessary to analyze the functions of each component or element, and trace back their direct and indirect impacts on the final outcome.

This paper aims to propose a decision-making framework to evaluate the effectiveness of ERS for oil spill. Identification failure modes will be done to influence the effectiveness of ERS. The failure means activities involved in response process do not complete their functions at a given time of contingency plan. Based on this, an analytical framework of effectiveness of ERS for oil spill is established in section 2, FMECA is adapted to define the structure and boundaries of ERS. The failure modes are identified to evaluate the subsystems and activities in oil spill emergency response. Risk ranking and results interpretation in ERS for oil spill is in section 3. A case study to validate the methodology framework is in section 4 and section 5 is the conclusion.

2 Methodology of evaluation

Evaluating the effectiveness of ERS should address the activities taken in response to underpin their impacts on final outcome. While FMECA is a technique used to analyse every component in sequence to determine their effects on the system and to classify each potential failure mode according to its severity (MIL-STD-1629A 1980). It was originally developed in 1940s by U. S. Military in MIL-P-1629 and widely used for military and space application today. FMECA includes a Failure Mode and Effect Analysis (FMEA) and Criticality Analysis (CA). FMEA is used for failure modes identification, the potential causes and effects. CA is used to compute the probability of failure modes against the severity of their consequences. The steps of FMECA process are as follows.

(a) Define the system and construct a system block diagram, which is to analyze the overall elements or components and their functions in operating system, and demonstrate their interconnection and interdependence among these components.

(b) Identify failure modes of operation system, to find "what could go wrong" and "why could it go wrong"; and then list all failure modes, no matter how few the occurrence is.

(c) Analyze failure occurrence probability. After identifying the failure modes and its potential causes, next step is to assess their occurrence probability to demonstrate their serious extent and priority of processing. The probability of failure modes can be estimated from the historical data basically. This brings difficulties in circumstances when information/past experience is lack or historical data is confidential. An estimation method for occurrence probability of the oil spill emergency failure modes should be exploited. The occurrence probability adopted in this paper is based on failure rate in MIL-STD-1629A, 1980. Since FMECA is a group decision behavior, the assessment information for risk factors is mainly based on experts' subjective judgments (Liu et al. 2001).

(d) CA. CA is to rank potential failure mode according to their severity and occurrence probability (MIL-STD-1629A 1980). The Risk Priority Number (RPN) is to demonstrate the risk of failure mode. It is a function of occurrence probability, the potential final effect (severity) and the likelihood of detecting. The RPN can be illustrated as follow:

$$\text{RPN} = S \times O \times D$$

where S is the rank of the severity of the failure mode; O is the rank of the occurrence of the failure mode; D is the rank of the likelihood of the failure detected.

The smaller RPN value the better, the larger the worse.

3 Establishing effectiveness evaluation model of ERS for oil spill

3.1 Defining structure and bounds of ERS for oil spill

According to analytical methodology to evaluate the effectiveness of ERS for oil spill, the first step is to define the bounds and functions of ERS for oil spill. Establishing a diagram describing the interrelationship and interdependent among various parts is premier in identifying failure modes in ERS for oil spill.

3.1.1 The structure of the ERS for oil spill

(1) Notification. While oil spill occurs, staff on site should report the information to related organization. The information should include causes of oil spill, location, estimated amount of oil spill and descriptions, actions have been taken, weather condition, etc. The site scene information is the basis of seriousness evaluating and decision-making.

(2) Evaluation. After receiving the information of oil spill, the slick trajectory should be modelled based on oil sources, wind and currents and predicted according to weather forecast, and the threats evaluation to some sensitive areas. The evaluation of oil spill

should through the whole response.

(3) Initiation: while receiving the oil spill report, the corresponding response tier should be initiated according to contingency plan, to build a response organization formed by relative organizations or other plan holders to direct the emergency response works accordingly. The key member leadership should be designated. Subsequently, based on the modelling of oil spill trajectory, the response decisions required should be made without hesitation and delay in the light of threats.

(4) Mobilization and clean-up. In this stage, the main work is to determine the available resources, deploy resources and ensure the sufficient resources logistics support in accordance with decision made by the response organization. The critical resources deployment and delivery are crucial parts in the period of emergency response. They support and implement through the whole response process, which comprises personnel and teams, physics materials, equipment, facilities and suitable response techniques.

(5) Review progress. It is mainly to ensure reevaluation through process to identify the oil spill situation under or out of control, which would highlight the response tier and resources scale up or down.

(6) Termination and plan view. While the oil spill accident is under control after evaluation, some after-action work should be processed. A review of the response should establish.

3.1.2 The diagram of the ERS for oil spill

The components in the process of oil spill are not separated, but interdependent and interrelated. Although each component in ERS for oil spill can afford their own function, any activity, such as oil spill information, initial evaluation, or decision-making would impact on other activities. Taking manage resources as example, it needs organizing local resources and dispatch from other locations. And the number and categories of physics material, equipment needed or technique chosen should be managed and organized based on the decision made by emergency response organization. The decision-making rely on the initial evaluation and assessment of resources needed by on-site responder further. Therefore, the stages or components in the ERS are interdependent and interrelated. The diagram is proposed to demonstrate the components interrelated and interdependent in ERS for oil spill (Fig. 1).

3.2 The failure modes identification and effect analysis in ERS for oil spill

The second phase is to identify the failure modes in ERS for oil spill. Failure mode can be defined as "the observable manners in which the component fails" (Charlies 1997). As a result, identifying failure modes of ERS for oil spill is required to break the system into "pieces" to capture every possible failure activity, no matter how minor probability it is.

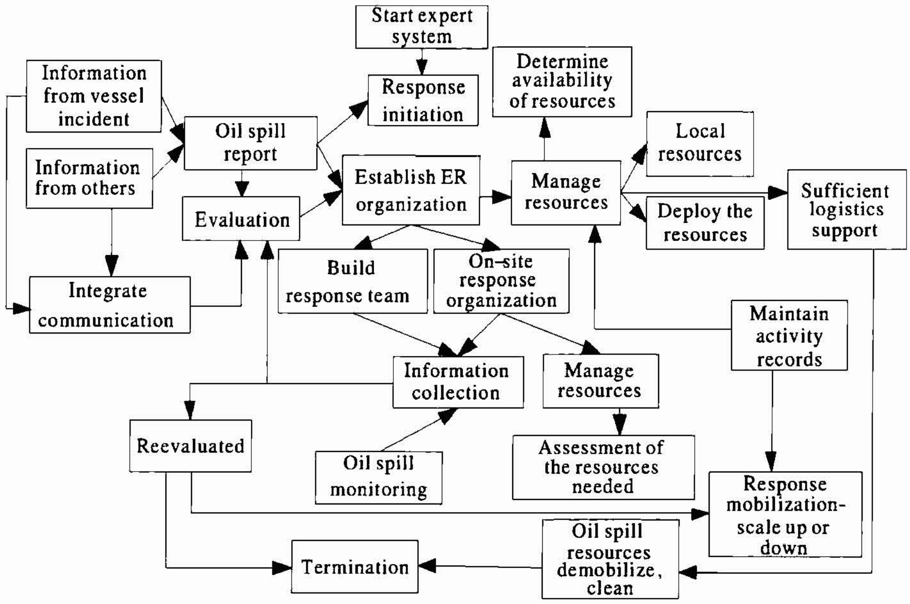

Fig. 1 Interrelated and interdependent of components in ERS for oil spill

The failure modes can be divided into two main classes, (1) response-termination failures, which would stop a response operation entirely, for example, the rescue and response cannot be started owing to extremely bad weather; (2) capability-reduction failures, which make a response operation less effective but do not halt response (Jackson et al. 2010). Most responses are attributed to the latter.

In oil spill emergencies, risk becomes dynamic. New risks emerge, previously recognised risks recede and the balance among risks changes continuously. Active risk assessment and management are on-going processes. The generic 17 identified failure modes can be seen in Tab. 1.

Tab. 1 RPN results of generic failure modes

Failure modes	RPN
Response communication channel or platform suffer from transmitting breakdown	43.70
Information share in the involved organizations incomplete	47.70
Decision-making delayed	265.70
Key member of leadership incompetent	140.80
Oil spill monitoring system fail	101.45
Lack of training of responder	288.75
Improper measures taken at the initial stage of response	165.20
Response resources are unavailable at the initial stage of response	118.10
Low coordination between the involved organizations	238.50
Crucial resources dispatch and deployment are delayed	201.50
No detailed map of sensitive water areas	8.30
Initial evaluation fails	239.20
Response team are insufficient	243.10
Improper technique to be chosen	113.80
Incomplete records of activities and cost	34.30
No corresponding waste oil treatment	19.80
Supplies that were assumed to be at the site had been used and not replaced	84.30

Failure occurr in every component during response due to the dynamic and high uncertainty. One failure may bring about "knock-on" effect and the potential causes may be diversified. For example, while the information of the oil spill is incomplete or lack of guide to direct evaluating the extent of seriousness, this failure would result in incorrect initial evaluation. No matter the initial evaluation is underestimated or overestimated the oil spill situation on spot, the initiate response tier and subsequent stages would be affected. The potential causes leading to this failure mode may be the first responder not supplying detailed information due to lack of knowledge or experience, or no special communication route access to the relative organization. And lastly may be caused by extremely bad weather. As a result, the failure modes are identified, the potential causes and effect resulted by the failure mode should be analyzed simultaneously.

3.3 Analysis of the occurrence probability and severity of failure modes

The analysis of occurrence probability and severity might be based on the historical data of past responses, or elicited from subjective experts. But the documented records during the response process are usually scarce and incomplete at present. The available data for quantitative analysis is scarce or far from ideal format. So it is somewhat difficult to evaluate the effectiveness of response. Therefore, the probability of occurrence in ERS for oil spill usually relies on domain experts (e. g. Delphi) to judge the possibility of occurrence and effect on the final outcome according to their experience and knowledgeable. In this section, five experts are chosen to investigate the ge-

Tab.2 Probabilities of occurrence and severity of generic failure modes

Item function	Failure modes	Potential effect of failure	Potential cause of failure	Weighting factor	Occurrence	Severity	Detection	RPN
Initiate response; Identify response, team members, their responsibilities and contact details; Make the response decisions required in the light of threats;	Decision–making delayed	Initiation delay; Mobilization delay and crucial resources are incapable of delivering and deploying in time; Insufficient logistics support;	Weighing the potential benefits of the intervention against possible collateral harm; No detailed and complete information;	0.10 0.25 0.30 0.15 0.20	7 6 7 6 6	7 7 6 7 7	6 7 6 6 6	265.7
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Coordination between organizations involved in the whole procedure of response	Low coordination between the involved organizations	Low response efficiency; Incapable of making decisions quickly; Delay the resources management; Incapable of integrating communication; Incapability of re–evaluate continuously; Prolong response time period	Lack of clarity in chain of command	0.10 0.25 0.30 0.15 0.20	7 6 7 7 8	6 6 6 6 6	4 6 7 5 5	238.5

neric failure modes of ERS for oil spill response. The weighting factor is assigned to each expert based on their experience, acknowledge and reputation, which is 0.10, 0.25, 0.30, 0.15, 0.20 respectively. The questionnaire is designed to include a potential generic failure mode in ERS for oil spill response, and answered according to the scale in MIL-STD-1629A 1980. The results can be seen in Tabs. 1, 2.

From the RPN results in Tab. 1, it can be seen that the failure modes, such as "crucial resources dispatch and deployment are delayed", "low coordination among the involved organizations" and "initial evaluation fails", are of the highest likelihood of failures in response process. The "lack of training responder", "decision-making delayed", "response team are insufficient", and "low coordination among the involved organizations" are related with person involved. This demonstrates the human errors are the main causes of failure modes in response. Meanwhile, resources and information are other area resultings in failure. During response, the person, resources and information are three crucial parts through the "whole life of the response". If any of them fails, not only affects their functions, but also has an impact on other activities. For example, "initial evaluation fails" means the organization does not get enough information of oil spill on spot. It would delay decision making or initiate improper response tier, and then make an impact on the dispatch and deployment of the emergency resources. The effectiveness of the ERS would be influenced in the end.

4 Experimental case study

Suppose there is a port named S alongside "Bohai" in China. An oil tanker with capacity of 2000 tons crude oil is aground in a water area nearby port S, from which approximately 10 tons crude oil leak into the sea. The weather condition is good. There is no harm on crew and the crew on board have taken actions to stop oil leakage further. The related organization receives the oil spill report, a responder team is constructed, and the corresponding response tier is started. The information about the oil spill is completed and the initial evaluation is appropriate. The point is that the local resources inventory is equipped to deal with less than 5 tons oil spill. The resources management should adopt "local + aid" modes which is coordinated with the neighboring emergency resources inventory. The outcome of this oil spill response is that the time to response oil spill is 12 hours longer than expected, which would result in the oil spill pollution area expanding.

1) Define the system and construct system block diagrams. In order to simplify the case, three components in the ERS are involved, initiation, mobilization and clean-up support. These three components are interdependent and interrelated with other components in ERS for oil spill shown in Fig. 1. The initiation component functions as starting the response activities on the basis of the evaluation results and managing resources; the mobilization as a support function in charge of managing resources from local emergency resources inventory and coordination from other location according to the decision made by the related organizations; the clean-up support completes the resources transported and delivers to the designated location in a given time to ensure the necessary resources support and avoid logistics disruption.

2) Identify the failure modes and their root causes in this response process. Focusing on three components of initiation, mobilization and clean-up support, the identified failure modes and potential causes are as followings.

(1) Poor coordination among the organizations involved in response hinders effective functioning of the accident command (Jackson et al. 2011), which would impact on establishing emergency response team, site scene response organization, and managing resources integrity and deployment; (2) The resources are delayed to designated area; (3) Captain on rescue ship is on holiday resulting in the disruption of resources delivery; (4) Logistics support from the neighboring emergency resources warehouse is delayed by poor coordinations; (5) The activities and related records are incomplete which results in the unclear of resources inventory and the duty chain is not clear in the contingency plan; (6) The receiving waste oil vessels are insufficient because there is no special waste oil vessel and the contracted vessel did

not arrive in time.

3) Evaluate the possibility of occurrence and severity of failure modes. According to the analytical framework, the probability of occurrence and severity are adopted to subjective-matter expert questionnaire to judge the scale of failure modes (Tab. 3).

Tab. 3 Probability of occurrence and severity of failure modes

Risk factors	FMECA experts	Failure modes					
		Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Occurrence	Expert A (0.10)	7	7	2	5	9	7
	Expert B (0.25)	4	7	3	8	8	7
	Expert C (0.30)	5	6	4	5	8	7
	Expert D (0.15)	8	4	4	6	9	8
	Expert E (0.20)	4	4	2	4	9	5
Severity	Expert A (0.10)	6	9	7	6	3	5
	Expert B (0.25)	6	6	7	6	3	4
	Expert C (0.30)	6	6	7	6	4	5
	Expert D (0.15)	7	8	6	6	2	6
	Expert E (0.20)	6	6	9	7	4	6
Detection	Expert A (0.10)	6	5	3	6	3	3
	Expert B (0.25)	7	6	4	7	3	4
	Expert C (0.30)	5	6	5	5	3	4
	Expert D (0.15)	4	6	5	7	4	5
	Expert E (0.20)	5	6	5	4	3	4
RPN		169.8	216.9	103.2	227.1	87.3	140.5

5 Conclusions

From the analysis of failure modes in ERS for oil spill, response effectiveness evaluation shows that the personnel, resources capacity and response coordination mechanism are extremely easy to fail and are vital to effective response. As far as the personnel in the response is concerned, two main aspects are involved, one is the key member with rich experiences in dealing with large-scale oil spill accidents, knowledgeable and high ability to corporation and coordination. The other is the response team with sufficient skilled and trained responders. The structure of responder is referred to percentage of the skilled, trained employees to others. The higher the percentage of the skilled and trained employee, the lower the percentage the responder risk themselves, the higher the response effectiveness and efficiency.

Another is the resource, which is the key support in the process of response, mainly referred to capability. From the analysis of the generic failure modes and case study, it can be concluded that the location of emergency resources, vehicles to collect resources to designated location, vessels to transport resources needed and receive collected waste oil should be equipped more than necessity to ensure enough capability to reduce the risk of failure and disruption and to increase response effectively; the records of activities are necessary because it would support the related information throughout the whole response process, which can be functioned as (1) the whole response process to clarify the deficiencies to be improved in the contingency plan; (2) historical data as an evidence to evaluate after action; (3) the resources consumption and as a reference to manage resources to ensure sufficient logistics support during the response process.

The most important aspect but not the last in ERS for oil spill is corporation and coordination mechanism. Large scale oil spill accident response is related with many organizations. Information share and corporation are the premier of response timely. As a result, the clarified responsibility chain should be addressed in the contingency plan.

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